X-ray Exposures of Electro-Deposited Photoresist for Conformal Lithography on Corrugated Surfaces

Frank T. Hartley[a], Chantal Khan Malek[b] and Steven Nguyen[b]

[a] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA.

[b] Center for Advanced Microstructures and Devices, Louisiana State University, 3990 West Lakeshore Drive, Baton Rouge, LA 70803.

ABSTRACT

Proximity printing using synchrotron X-ray lithography provides high resolution pattern transfer with large depth of field, low diffraction effects and no reflection from the substrate. Electro-plating of photo-resist allows deposition of thin, uniform films over geometrically complex and topographically diverse, electrically conductive surfaces. Two electro-deposited photoresists produced by Shipley, EAGLE 2100 ED negative tone and PEPR 2400 positive tone resist, have been tested with X-rays demonstrating micron pattern transfer over depths-of-field in fractions of millimeters.

Keywords: Electro-deposited resist, X-ray lithography, Deep depth-of-field

1. INTRODUCTION

Ultraviolet (UV) illuminated photolithographic processes cannot maintain sub-micron definitions from surface mesa through the bottom of deep trenches (> 10 μm) or over large variations in feature topography due to diffraction effects or limited depth of focus of the optical system. However, shadow printing with X-rays is known to be able to pattern photo-resist covering surfaces of extreme topographical variation with reduced diffraction effects and no substrate reflection.

Traditional centrifugal spun photoresist application does not give uniform, conformal coatings over substrates with extreme or complex topography. Alternatively, electro-plating provides a straightforward means of depositing thin, uniform photoresist films over geometrically complex and topographically diverse, electrically conductive surfaces. Positive and negative working water-borne, electro-deposited, UV photo-sensitive resists are used in patterning circuit wiring boards. X-ray sensitivity trials were undertaken with both Shipley Company Inc. (SCI) PEPR 2400 positive tone and Eagle 2100 ED negative tone resists at the Center for Advanced Microstructures and Devices (CAMD) LSU synchrotron.

The correct exposure dose, development technique and development conditions were established for both SCI electro-deposited resists. X-ray lithography was demonstrated for both photoresists.

2. EXPERIMENTAL

2.1. Photolithography limits

Conventional Ultraviolet (UV) illuminated photolithographic processes for the precise (sub-micron) patterning of micro-electronic and micro-mechanical features is very limited in accommodating variations in surface topography of greater than tens of microns. Conventional photolithography is limited by diffraction and/or depth of focus in its capability to image small features over large variations in topography, typically at least several microns for 500 micron height variation. However, X-rays are routinely used to pattern thick photo-resist (10 micron to cm) with sub-micron to micron spatial definition, as for example in the LIGA process[1]. The same masks and high energy X-ray illumination can be used to pattern thin layers of photo-resist covering surfaces of extreme topographical variation.

2.2. Electrodeposited resist

Photoresist is traditionally applied by means of centrifugal spinning equipment. However, spun resist streaks over uneven surfaces and, for extremely topographically diverse surfaces, fills deep crevices and misses elevated mesas. Electro-plating is the most straightforward method of depositing photo-resist films uniformly over geometrically complex and topographically diverse conductive surfaces. It also generates less substrate stress and can accommodate a wide variety of substrate sizes and shapes that are determined by plating bath geometry, not centrifuge. However, such depositions can only be made onto electrically conductive surfaces. Shipley Company Inc. (SCI) produces both positive and negative resists for UV exposure[2,3]. These resists have been developed for single-pass conveyor-belt type processing of circuit boards. The positive working water-borne resist is the PEPR 2400, which is applied by direct current anodic electro-deposition. The negative working aqueous emulsion resist, Eagle 2100 ED, is applied by direct current cataphoretical electro-deposition. In both cases, the charged resist components migrate to, and are uniformly deposited upon, an electrically conductive substrate. Both electro-deposited photoresists are insensitive to yellow light. The positive working PEPR 2400 and the negative working Eagle 2100 ED have their peak photo-sensitivity over the 380-420 nm and the 340-400 nm bandwidths respectively. To our knowledge, no one had previously tried exposing them with X-rays.

The samples used in our experiments were prepared by SCI on copper coated silicon wafers, circuit boards and circuit boards containing through-holes.

2.3 X-ray Lithography

All X-ray exposures were performed either on the XRLM3 beamline for hard X-ray lithography or the XRLC1 X-ray lithography beamline[2] at the CAMD 1.5 GeV storage ring. The XRLC1 beamline is optimized for high resolution IC printing with XRL in thin resists (< 10 μm). It is equipped with two parallel plane mirrors operating at 1.5^0 grazing incidence to cut-off the high energy part of the beam. The spectrum transmitted through the 25 micron thick Be window is broad-band in the 7 Å - 14 Å range with an integrated power density of 68 mW/horizontal-cm with the storage ring operating at 1.3 GeV and 100 mA. The "XRLM3" beamline has a harder energy spectrum. It has no optics and the spectrum transmitted by the 125 micron thick Be window is in the 1.5 Å - 6 Å range with an integrated power density of 415 mW/ horizontal-cm with the storage ring operating at 1.3 GeV with 100 mA beam current.

Wafers were scanned vertically through the beam, the X-ray dose being calculated by the storage ring current integrated over time. Simple X-ray masks made from free-standing mesh of absorbing wires were used for the first tests, then X-ray test masks made by MCNC were employed. The proximity gap was set by clamping mask and wafer together with spacers. No Stouffer step tablet arrangements exist for X-ray exposure determination. The doses were calculated from the Transmit program.[4] In order to find correct process parameters, one of the following process parameters, exposure dose and development time, were varied, the rest of the parameters being fixed.

As a starting point, an integrated exposure intensity of $3KJ/cm^2$ at the bottom of the resist was tried for both positive and negative resists. This exposure dose corresponds to good conditions for PMMA and rendered the mask pattern visible before development in the electrodeposited resists, which is a sign of over-exposure (SCI private communication).

2.3.1 Eagle 2100 ED Negative Working Resist

The exposure doses on the XRLC1 beamline were then progressively decreased for a series of Eagle 2100 ED negative resist coated substrates until the correct dose was determined. The Eagle 2005 developer produced slag which covered the substrate and was not ameliorated by either ultrasonic or megasonic agitation. Replacing immersion development by spray development solved this problem. The X-ray dose was progressively reduced from a $3KJ/cm^2$ intensity to a $20J/cm^2$ level with a metal mesh mask. Next the feature rich MCNC test pattern mask (consisting of a 2.1 micron thick silicon wafer and a 4.2 micron thick gold absorber) was used. Figure 1 shows electron microscope enlargements of developed images of the extremely small featured parts of the printed test pattern after 60 J/cm^2 exposure dose and 150 seconds of jet spray development at 40°C. The clarity of the fine features in these images attests to the suitability of this Eagle 2100 ED negative working photoresist for thin film (5 μm) hard X-ray lithography. The exposure dose for the Eagle 2100 ED resist was found to be 120-150 times the dose ($400mJ/cm^2$) required at its peak UV (340-400 nm) sensitivity.

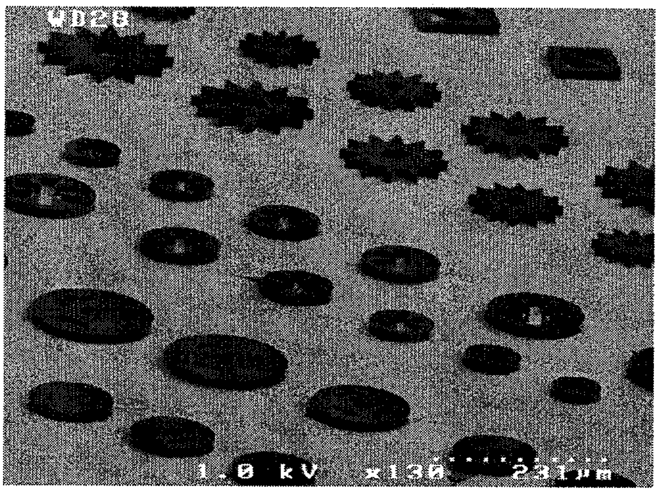

Fig. 1-a

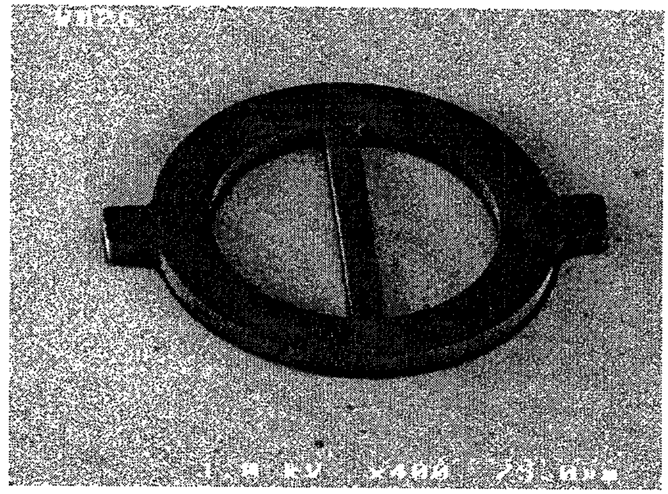

Fig.1-b

Fig. 1: X-ray lithography of Eagle 2100 ED resist on smooth sputtered copper coated silicon wafer a) overview, b) close-up of a feature.

2.3.2 PEPR 2400 Positive Working Resist

The high energy XRLM3 beamline was used for the positive PEPR 2400 resist. At an exposure dose of 2536 J/cm^2 on the XRLM3 beamline with the MCNC test mask (2.1 micron silicon membrane and a 4.2 micron thick gold absorber) and development by the jet spray method for three minutes at 36^{o}C (same as required for UV exposure). Clear, clean and high contrast images were obtained (Fig. 2). However, some erosion of the unexposed resist is observed.

Electro-deposited resist with 7-8 micron thickness was applied to copper coated fiber glass circuit boards and through-hole plated vias to provide extreme topological variation. In this trial a LIGA test mask (2 micron silicon membrane and a 10 micron thick gold absorber) was used because of its denser absorber and linear test patterns. The fine features and clarity of these developed images across and into cavity attests to the high resolution of the PEPR-2400 positive working photo resist for thin film (8µm) exposed with hard X-ray lithography, despite the roughness of the copper coated substrate and granularity of resist. This represents a most encouraging demonstration of large depth-of-field lithography afforded by X-rays.

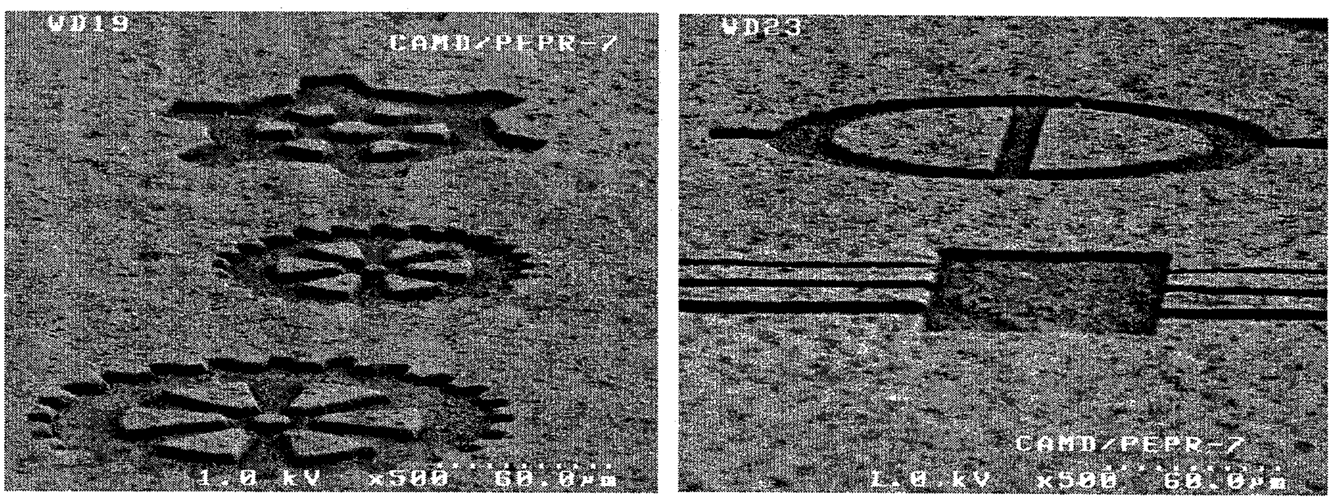

Fig. 2 X-ray lithography of 5 micron thick PEPR 2400 after development.

3. OUTLOOK

Both the Eagle 2100 ED negative working resist and the PEPR 2400 positive working resist were found to be sensitive to X-rays but several orders of magnitude less sensitive than the peak UV sensitivities of the resists. The electro-deposited photoresists conformally coated rough copper coated fiber glass circuit boards and the extremely rough side walls of copper coated vias. The X-ray lithography was not diffraction limited and the lack of any reflections from substrate and interface reflections ensures sub-micron resolution in pattern transfer over the geometrically complex or topologically diverse surfaces if the resist allows for it. The clarity of pattern projection from surface down into via cavity demonstrates a depth-of-field in excess of 100 micron. Indeed the patterning depth was limited by copper ridge shadowing not any optical constraints.

Having established that electro-deposited photoresists are X-ray sensitive the next activity involves patterning surfaces with known topographical diversity and empirically determining feature resolution and depth of field. Erosion of patterned copper and measurements of finesse of actual pattern transfer will provide qualification of these resists with X-ray lithography.

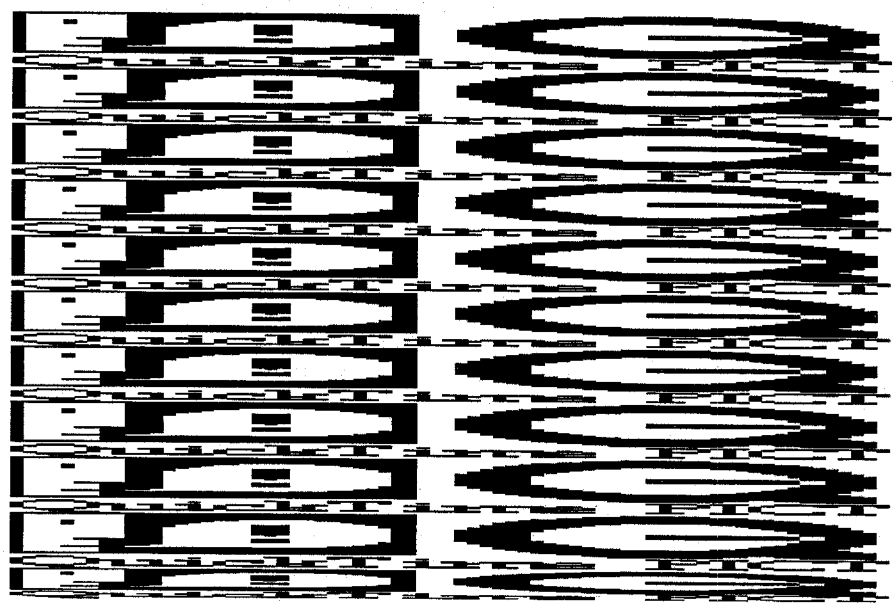

Fig. 3: X-ray lithography of PEPR 2400 down a via 100 μm deep on rough copper.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Jill Steeper, of Shipley Company Inc., for undertaking the electro deposition of both photo-resists; Zhowg-Geng Ling, of CAMD, for his valuable assistance in performing these trials; and Robert Wood, of MCNC, for the loan of LIGA masks for use in these trials. This work was carried out by Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA and by the Center for Advanced Microstructures and Devices (CAMD) Louisiana State University.

REFERENCES

1. E. W. Becker, W. Ehrfeld, P. Hagmann, A. Maner, D. Munchmeyer, "Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming, and plastic moulding (LIGA process)", *Microelectronic Engineering* 4, 35-56 (1986).
2. S. Linder, H. Baltes, F. Gnaedinger, and E. Doering, "Photolithography in anisotropically etched grooves", *IEEE Proc. MEMS*, San Diego, CA, p. 38-43 (1996).
3. D. A. Vidusek, "Electrophoretic photoresist technology: an image of the future-Today," *Circuit World*, **Vol. 15**, 2, (1989).
4. C. Khan Malek, Y. Vladimirsky, O. Vladimirsky, J. Scott, B. Craft, and V. Saile "X-ray microfabrication at the Center for Advanced Microstructures and Devices," *Rev. Sci. Instrum.* **67**, No9, Workshop 1, 1-6 (1996).
5. F. Cerrina, SHADOW, University of Wisconsin-Madison, Sept. 1989.